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Assessing coastal vulnerability: Development of a combined physical and economic index

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ABSTRACT

As a consequence of climate change, coastal communities worldwide are subject to increased risk from sea-level rise and more intense storms. Therefore, it is important for coastal managers to have focused site specific data on present and predicted climate change impacts in order to determine shoreline vulnerability. There are few UK studies that characterise coastal vulnerability, while nearly all global work has concentrated on geomorphological and to a lesser extent, socio-economic aspects. In response, the present study developed a new Physical Coastal Vulnerability Index (PCVI) and applied it to eleven UK sites, seven in England, three in Wales and one in Scotland. PCVI results were then compared and contrasted with a new Fiscal Coastal Vulnerability Index (FCVI), which enabled coastal areas to be visually classified in one of four categories to inform relative risk. Both indices were subsequently integrated into a Combined Coastal Vulnerability Index (CCVI). Results showed that Great Yarmouth and Aberystwyth were highly vulnerable, while Llanelli and Lynmouth were least vulnerable, and the importance of integrating both indices is demonstrated by modified overall vulnerability assessments. Therefore, CCVI provides a simple to use shoreline monitoring tool which is particularly suitable for assessment of risk. The indices support coastal planning, including intervention or no active intervention policies, and thereby benefitting a range of stakeholders. CCVI works at local, regional and international scales, and identifies vulnerable locations. Consequently, these indices will inform management strategies to improve coastal resilience under various sea level rise and climate change scenarios.

1. Introduction

Coastal zones are highly dynamic and are susceptible to natural hazards, due to the diverse climatic changes that are occurring around the world (Zsamboky et al., 2011; Arkema et al., 2013). The world's coastlines have different geographical characteristics that influence the generation of trade and other coastal activities and make significant contributions to the economies of countries (Kantamaneni, 2016a). Increases in coastal disasters, particularly flood events, impose large socio-economic costs, particularly in populated estuaries, low-lying coastal urban areas, and islands, and these are important communal hotspots of vulnerability (Hinkel et al., 2010). Threats to coastlines occur where substantial growth on the land near the sea is affected by shape and biophysical features (Carter, 2013), while Newton et al. (2012) introduced a syndrome-based method of assessing coastal vulnerability that emerged from concerns related to the impacts of climate variations on coastal zones, suggesting that multiple stressors impact coastal systems worldwide in several ways. The impacts of regional and global climate changes, sea-level rise, and weather fluctuations, alongside terrestrial processes, represent serious threats to all coastal communities (Oliver-Smith, 2009; Handmer et al., 2012). Global trends in sea-level rise have an effect on the UK, particularly along the Norfolk and Suffolk coastlines in southeast England, where records show a historic rising trend (Doody and Williams, 2004; Pye and Blott, 2006; Brooks et al., 2012). According to UNEP (2013), the UK coast has been strongly altered, and the UK's shoreline is one of the most degraded of any country in the world. Therefore, coastal vulnerability assessments are very important when consideration is given to the management and future development of coastal regions, both in the UK and elsewhere across the globe.

Considerable literature exists from around the world on geomorphological and physical coastal vulnerability (Gornitz and Kanciruk, 1989; Gornitz, 1990; Gornitz et al., 1994; Abuodha and Woodroffe, 2010; Balica et al., 2012; Kumar and Kunte, 2012; Wang et al., 2014;

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Pramanik et al., 2016; Nguyen et al., 2016; Islam et al., 2016). However, there are few corresponding studies on socio-economic vulnerability (Cutter et al., 2003; Vincent, 2004; Schröter et al., 2005; Rygel et al., 2006; Hahn et al., 2009). Similarly, there are UK studies (McLaughlin et al., 2002; McLaughlin and Cooper, 2010; Denner et al., 2015; Kantamaneni, 2016a; Kantamaneni, 2016b), but none assess combined physical and economic vulnerability. Therefore, the present study assesses the physical and economic vulnerability of eleven UK sites of varying physical and economic characteristics; the locations chosen from academic articles and reports of flooding and loss. By assessing and integrating each site's Physical Coastal Vulnerability Index (PCVI) and Fiscal Coastal Vulnerability Index (FCVI), analyses will enable the comparing and contrasting of physical, economic and combined vulnerabilities from multiple perspectives, including ranking of the eleven vulnerable UK coastal areas.

2. Study areas

Consistent with the work of Kantamaneni (2016b), eleven vulnerable coastal sites in the UK with diverse anthropogenic, physical and socio-economic characteristics have been selected for coastal vulnerability assessment. Of these sites, seven are in England, three are in Wales, and one is in Scotland (Table 1; Fig. 1).

2.1. Description of study area locations

Spurn Head, primarily has the form of a sand and shingle spit covered by dunes, together with an area of till and alluvium to the north (May and Hansom, 2003). Contributing to the spit's sediment budget, low till cliffs are being eroded at rates in excess of 2.5 m yr-1 at its northern end. Macro-tidal tides with a tidal range of 6 m influence sediment deposition along the frontal lobe of the spit that can erode at rates of between 1 m and 2 m yr-1 (Quinn et al., 2009). The lack of any type of coastal defences make this region more vulnerable to erosion. ***Hallsands***, a combination of gravel extraction, high wave energy and high tide conditions have resulted in rapid coastal erosion, which makes Hallsands one of the most heavily eroded sites in the UK. ***Lynmouth,*** severe coastal flooding events often cause damage in the Lynmouth area, due to rapid climatic change scenarios (Scrase and Sheate, 2005). Changes in land use and management, urban development in the catchment and sea-level rise cumulatively affect the frequency and magnitude of flooding in this area (Enviornemt Agency, 2012). ***Happisburgh,*** coastline is exposed to waves from multiple directions, and it is especially vulnerable to storms generated from the north, as there is no fetch limitation in this direction (Thomalla and Vincent, 2003). Storm waves erode the glacial till at the base of the cliffs, causing collapse and rapid erosion; more than 260 metres of coastline has retreated in recent years (BGS, 2014). Existing costal defences (wooden revetments) are not strong enough to protect the coast from different varieties of hazards in this area. ***Dawlish,*** coastal strip is more than 6 km in length between Teignmouth and Dawlish has been highly vulnerable to recurrent closures due to high sea waves and storm attacks since it was constructed. This became especially apparent during the 2013/12 winter storms when the sea was breached and properties were damaged (Dawson et al., 2016). In the last 2000 years, the sea-level rise along the south coast has been ~0.9 mm/yr. (Dawson, 2012).

Great Yarmouth, a low-lying coastal town constructed on a spit, which is made up of varying proportions of sand and gravel. The region has a history of coastal flooding, and this situation is not helped by the fact that the river Yare separates the spit from the mainland at its western end (Nicholls et al., 2007). Landslides and erosion are common problems in this area. ***Skegness***, is a coastal town in Lincolnshire district in England. It has been subject to erosion and general retreat for several centuries (Dugdale and Vere, 1993). The high water table and low-lying landscape of this region, in conjunction with the increased risk associated with sea-level rise, postglacial adjustment (forebulge collapse) and storm surges, intensify the area's physical vulnerability to the effects of climate change (Zsamboky et al., 2011). ***Benbecula,*** exposed to North Atlantic Ocean winter storms and waves (Wolf and Woolf, 2006; Dawson et al., 2007). Accordingly, high waves and coastal erosion are the most significant problems in this area, and it is one of the highly eroded sites in the UK (Kantamaneni and Phillips, 2016). ***Aberystwyth*** coastal strip is > 2 km long and is mostly reinforced by hard sea defences. The sea front, which is exposed to south-westerly storm waves, has a history of erosion and sea defence breaches that spans several decades. The most recent storms occurred in late 2013 and early 2014, during which the coastlines of the UK were severely affected by an exceptional run of winter storms, culminating in serious coastal damage and widespread flooding (Slingo et al., 2014). ***Port Talbot,*** coastline is backed either by natural dune systems or retaining structures, but many of the commercial and residential properties built in this relatively low lying area are at risk of flooding. Strong winds and tides generated in the Bristol Channel contribute to a high-energy wave environment (Allan et al., 2009). Prevailing winds emanate from the southwest; the macro-tidal environment has a spring tidal range 7.5 m (Phillips and Crisp, 2010), and storm waves > 5.5 m with periods > 8.5 s are not uncommon in this region (Thomas et al., 2015). ***Llanelli,*** coastline is mostly backed by coastal defences and recent storm events have severely damaged the coastal paths and rail infrastructure and caused damage to several newly constructed dwellings (Denner et al., 2015). It is acknowledged that continuous flooding in the area has resulted from increases in impervious surfaces that resulted from the construction of new developments, increases in the sewage base load caused by housing stock expansion, and the co-occurrence of high tides with heavy rainfall (CCC, 2007).

Table 1
Vulnerable coastal sites chosen for detailed assessment.

England	Wales	Scotland
Spurn Head	Port Talbot	Benbecula
Skegness	Llanelli	
Happisburgh	Aberystwyth	
Great Yarmouth		
Hallsands		
Dawlish		
Lynmouth		

3. Methodology

A severe storm and extreme wave event coinciding with an equinox caused significant infrastructure damage along the KwaZulu-Natal (South Africa) coast. Subsequently, Palmer et al. (2011) developed a literature based PCVI by assessing five physical factors that affect shoreline vulnerability, i.e. beach width, dune width, distance to 20 m isobath, distance of vegetation behind back beach and percentage rock outcrop. These were given scores based on predefined thresholds with parameter and estuary weightings completing the assessment framework. This framework was then applied to 50 m by 50 m cells along the KwaZulu-Natal shoreline, which gave a measure of relative shoreline vulnerability based on an 'very low', 'low', 'moderate' and 'high' scoring system (1–4). Denner et al. (2015) modified this for the Loughor Estuary (Wales, UK) by dividing 11 km of the coastline into 100 m × 10 m cells and subsequently ranking relative vulnerability according to 'very low', 'low', 'medium', 'high' and 'very high'. Consequently, they were able to identify relative coastal risk along different segments of the Loughor Estuary. Denner et al. (2015) methodology retained Palmer et al. (2011) five physical factors, but in the current study, a new PCVI was developed which integrated two additional physical parameters: 'distance of built structures behind the back beach' and 'sea defences'. These parameters affect shoreline vulnerability and their thresholds were determined from expert opinion. Consequently, Table 2 details the

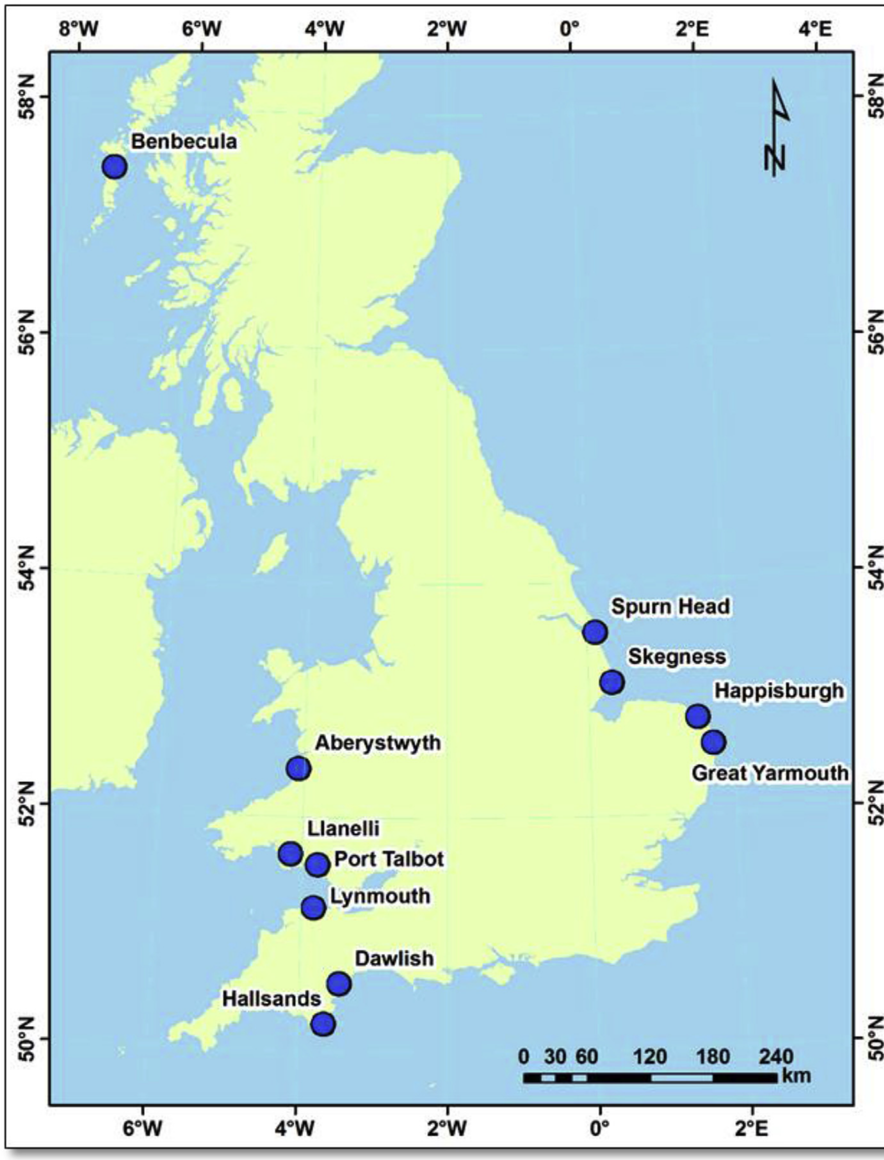

Fig. 1. Study area locations used for coastal vulnerability assessment.

seven PCVI parameters used to assess physical coastal vulnerability, together with assessment criteria based on Palmer et al. (2011) 'very low', 'low', 'moderate' and 'high' scoring system.

Economic parameters were originally obtained using Balica et al. (2012) indicator-based methodology where following assessment and trend analyses 20 initial parameters were reduced to the six considered most significant, i.e. 'Commercial properties', 'Residential properties', 'Economic value of site', 'Population', 'Coastal erosion' and 'Flood impact'. Data was collected from various organisations regarding number of properties, economic value of location, current market prices, population and flooding frequency. These values were then used to determine economic thresholds and classifications 'extremely low', 'low', 'moderate', 'high' and 'extremely high', enabled a semi-quantitative assessment of fiscal vulnerability. The FCVI (Kantamaneni, 2016b) was subsequently integrated with PCVI results to produce a combined coastal vulnerability index (CCVI). Using 0.5 km cells

Table 2
Physical parameter ratings associated with different levels of vulnerability.

Physical Parameter	Designated Symbol	Physical Vulnerability Value			
		Very Low (1)	Low (2)	Moderate (3)	High (4)
Beach width	a	> 150 m	100–150 m	50–100 m	< 50 m
Dune width	b	> 150 m	50–150 m	25–50 m	< 25 m
Coastal slope	c	> 12%	12–8%	8– 4%	< 4%
Distance of vegetation behind the back beach	d	> 600 m	200–600 m	100–200 m	< 100 m
Distance of built structures behind the back beach	e	> 600 m	200–600 m	100–200 m	< 100 m
Rocky outcrop	f	> 50%	20–50%	10–20%	< 10%
Sea defences	g	> 50%	20%–50%	10–20%	< 10%

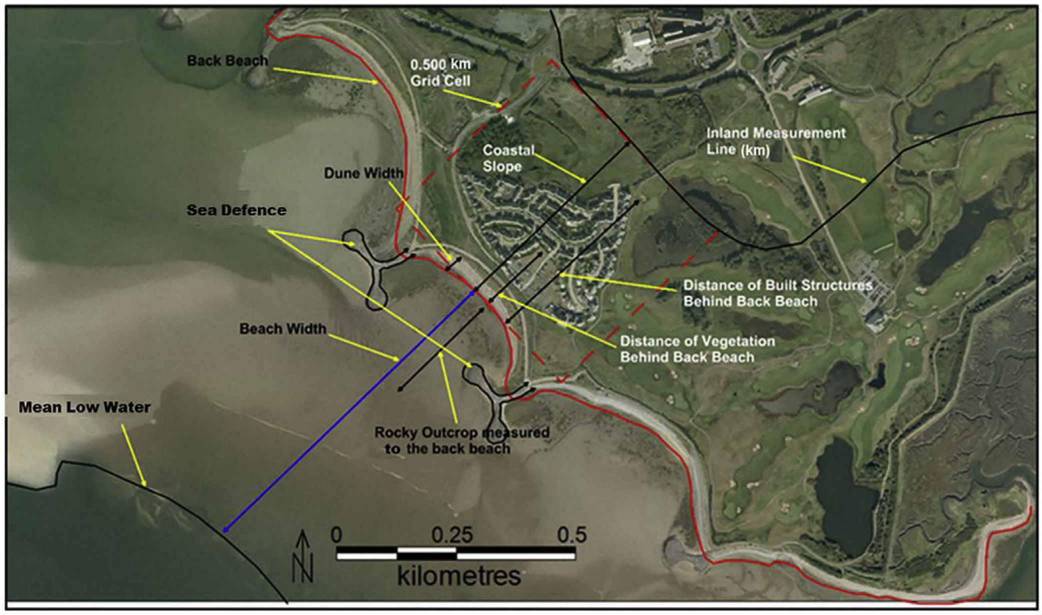

Fig. 2. Transect line and 0.5-km coastal cell.

(Fig. 2), this new methodology evaluates coastal vulnerability from multiple perspectives as explained in the following sections.

3.1. PCVI

3.1.1. Physical parameters and measurement

Beach widths were measured from the back beach (Fig. 2) co-ordinates to the mean low water level (MLW) mark, using spatial datasets represented in a GIS. Owing to variations in tidal range and the presence in some locations of deep-water channels running adjacent to the shoreline (for example, at Llanelli), the MLW mark differs greatly. Ordnance Survey Digimaps and spatial data were used for measurement of this parameter. **Dune width** was gauged as the length between a predetermined back beach coordinate and the nearest infrastructure (built structure) or entirely vegetated zone. Ordnance Survey Digimaps and GIS spatial data were used for measurement of the dune width (Fig. 2). **Elevation profiles** extracted from Google Earth Pro were used to measure the coastal slope parameter (Fig. 2). A distance of 500 m (as shown in Fig. 2) was selected to measure the **distance of vegetation behind the back beac**h for the present study. In areas where the foliage did not spread beyond built structures, the vegetation was measured to that point. Built structures, such as paths, roads, and railways, were measured for their widths and deducted from the total vegetation if there were significant expanses of vegetation beyond these structures (Fig. 2). Furthermore, a distance of 500 m was also selected to measure the **distance of built structures,** such as paths, roads, railways, and private and commercial buildings, behind the back beach. In areas where foliage was encountered, the vegetation was measured, and the total vegetation was deducted from the built structure expanse (Fig. 2). Ordnance Survey Digimaps and spatial data were used for measurement of these two parameters. Regarding the rocky outcrop parameter, the coastal landforms of particularly rocky coasts are least vulnerable to sea-level rise and the impacts of coastal erosion (Gornitz, 1991). Most of the study sites examined in the present study do not display extensive rocky outcrops. Therefore, the widths of these features within individually surveyed cells were measured. These values indicate the percentage of rocky outcrop along a transect line between MLW and the back beach coordinates, and all measurements were performed using a combination of GIS and orthophotographs (Fig. 2). Sea defences (e.g., rock revetments, solid walls, timber, natural, and rock) were selected as representing one of the significant parameters for this study, and these were based upon the percentage of shoreline coverage within each cell (Fig. 2).

3.1.2. Thresholds of physical coastal vulnerability

Denner et al. (2015) noted that physical parameters have various stages of response or offer different levels of coastal protection, based upon the significance of the impact. Therefore, all parameters were weighted according to their value and the corresponding perceived level of risk. The additional parameters, i.e., distance of built structures behind the back beach and sea defences, were included in this study to highlight the susceptibility of coastlines to flooding and other associated hazards. It was also essential to modify the method of Denner et al. (2015) to reveal the unique physical characteristics of the study locations. This amendment was needed because most of the study locations were not adequately protected or were only partially protected by rocky outcrops and sea defences. The thresholds of the two new parameters were determined based on collected data, and the remaining parameters' values were determined based upon the study of Denner et al. (2015). Each parameter was assigned a ranking score between 1 and 4. To assess vulnerability quantitatively, the individual measurements were then compared and assigned a ranking from very low (1), low (2), moderate (3) to high (4). Once the rankings had been assigned, these values were then summed for each location to provide a relative CVI score, where PCVI = a + b + c + d + e + f + g, where each letter was equal to the ranking score for each parameter and ranged from seven to 28. These scores were compared with Table 3 in order to categorise the total relative level of physical vulnerability for each cell, and subsequently each assessed location. If any cell did not receive a score for any value for that condition, the cell in question was

Table 3
Vulnerability level ratings grouped by total relative vulnerability score.

Total Relative Vulnerability Score	Vulnerability
< 12	Very Low
12–15	Low
16–18	Moderate
19–23	High
24–28	Very High

Table 4
Coastal economic vulnerability parameters and threshold values (m, millions).

Fiscal Parameter	Fiscal vulnerability value				
	Extremely Low (1)	Low (2)	Moderate (3)	High (4)	Extremely High (5)
Commercial properties (a)	< 2 m	2–10 m	> 10–30 m	> 30–70 m	> 70 m
Residential properties (b)	< 30 m	30–80 m	> 80–130 m	> 130–180 m	> 180 m
Economic value of site (c)	< 10 m	10–50 m	> 50–100 m	> 100–150 m	> 150 m
Population (d)	< 500	500- 2000	> 2000–5000	> 5000–10,000	> 10,000
Coastal erosion (e)	< 0.3 m	0.3–2.5 m	2.6–5 m	> 5–9 m	> 9 m
Flood (event) impact (f)	< 3 m	3- 9 m	> 9–15 m	> 15–35 m	> 35 m

given the highest PCVI value, i.e., 4.

3.2. FCVI

The FCVI was developed and applied to 11 coastal locations by Kantamaneni (2016b). In this methodology, six parameters (reproduced in Table 4) were used to evaluate the economic vulnerability of these 11 coastal hotspots. Accordingly, transect baselines were drawn across the frontage (i.e., parallel to the coast) on each vulnerable coastal site, and 1-km grid squares (cells) were drawn inland, from which detailed measurements based upon each parameter were recorded within each identified cell (Fig. 3).

To quantitatively assess vulnerability, individual cell measurements were assigned a ranking score of extremely low (1), low (2), moderate (3), high (4) or extremely high (5) (Table 4). After these had been applied, values were then summed at each location to provide a relative CVI score, using FCVI = a + b + c + d + e + f, where a-f represent the ranking scores for the parameters. The FCVI value ranges between a minimum value of 6 and a maximum of 30 (Table 5). These scores were utilised to assess the level of economic vulnerability for each location.

3.3. CCVI

In a final step, the PCVI values were amalgamated with the FCVI values to form a combined physical and economic vulnerability index, i.e., the combined coastal vulnerability index (CCVI). This was achieved by averaging the total scores for each location (equation (1)), and this procedure yielded values between 1 and 28.

Table 5
Vulnerability level ratings grouped by total relative vulnerability score.

Total Relative Vulnerability Score	Vulnerability
12–15	Low
16–18	Moderate
19–22	High
23–30	Extremely High

$$CCVI = \frac{\frac{(\sum PCVI)}{N} + \frac{(\sum FCVI)}{N}}{2} \tag{1}$$

where N = number of cells contributing to total PCVI and FCVI scores respectively.

To assess each location's combined physical and economic vulnerability, the computed scores for each location were averaged (summed and divided by two), giving a value between 1 and 29, according to the equation below.

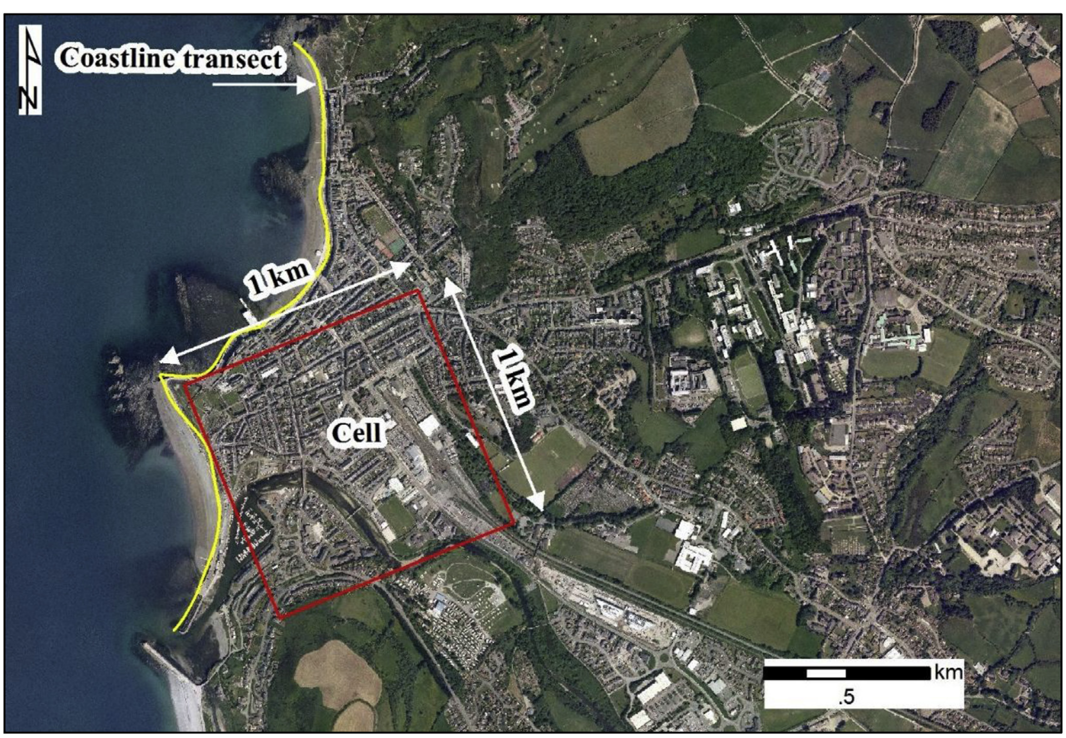

Fig. 3. 1-km coastal cell drawn on transect line.

Table 6
Site locations and numbers of associated cells.

Location	Coastal length considered (km)	Cell range	Total assessed cells
Spurn Head	3	1–6	6
Hallsands	4	7–14	8
Lynmouth	2	15–18	4
Happisburgh	4	19–26	8
Dawlish	5.5	27–37	11
Great Yarmouth	14	38–65	28
Skegness	11.5	66–88	23
Benbecula	7.5	89–103	15
Aberystwyth	2.5	104–108	5
Port Talbot	12	109–132	24
Llanelli	13	132–158	26
	Total length = 79		**Total cells = 158**

$$CCVI = \frac{(Average\ PCVI + Average\ FCVI)}{2}$$

Note that 29 is the average value of the maximum relative values of the PCVI and the FCVI, i.e.,

Maximum PCVI relative score + Maximum relative FCVI score

$$\frac{(28 + 30)}{2} = 29$$

4. Results

4.1. Analysis of the PCVI values

Coastal cell measurements were performed for each location in accordance with the procedures described in the methodology section. Each shoreline frontage was divided into 0.5-km cells. In total, 158 cells along 79 km of coastline were identified (Table 6). The three locations in Wales were associated with circa 27.5 km of coastline (55 cells), the seven locations in England were associated with circa 44 km of coastline (88 cells), and the single Scottish region was associated with circa 7.5 km of coastline (15 cells). Table 6 shows the individual case study sites and the numbers of associated cells used for the evaluation of physical vulnerability. These 11 coastal regions were critically analysed from a physical perspective by applying the PCVI.

There are considerable variations between the 158 cells in terms of the associated index values. The average **beach width** was 239.1 m, which lay between the maximum value of 1900 m recorded for cells 143 and 144 (Llanelli) and the minimum value of 1.4 m recorded for cells 44 and 45 (Great Yarmouth). Moreover, 47% of the cells were associated with values lower than 50 m, reflecting high vulnerability. The average **dune width** was 97.1 m, which lay between the maximum value of 515 m recorded for cell 111 (Port Talbot) and the minimum value of 9.5 m cell 74 (Skegness); 71% of the cells contained no dune landforms. The average **coastal slope** was 3.9%, which lay between the maximum value of 48% recorded for cell 18 (Lynmouth) and the minimum value of 0.4% recorded for cell 66 (Skegness); 70% of the cells were associated with below-average values. The average **distance of vegetation behind the back beach** was 243 m, which lay between the maximum value of 500 m recorded for cells 19, 41 and 112 (Happisburgh, Great Yarmouth and Port Talbot respectively) and the minimum value of 4 m recorded for cell 23 (Happisburgh); however, vegetation cover was recorded for 85% of the cells. The average **distance of built structures** behind the back beach was 235 m, which lay between the maximum value of 500 m recorded for cell 13 (Hallsands) and the minimum value of 2.4 m in cell 155 (Llanelli), and only 10% of the cells contained no built structures. The **average rocky outcrop** was 27%, which lay between the maximum value of 100% recorded for Aberystwyth and Benbecula and the minimum value of 0.8% recorded for cell 146 (Llanelli); 72% of the cells did not have rocky outcrops. The average recorded **sea defence** coverage was 81.32%, which lay between the maximum value of 100% that represents coverage of entire cells (this condition is noted at Dawlish, Skegness, Aberystwyth, Port Talbot, Llanelli and Benbecula) and the minimum value of 1% recorded for cell 120 (Port Talbot). Importantly, sea defence structures were absent from 63% of the cells.

4.1.1. Application of physical vulnerability scores

There are significant variations between the 158 cells with respect to their PCVI values. The average CVI score for **beach width** was 2.3, and the highest was four, which was recorded for 48 cells (30%). Most of the highest values were recorded at Llanelli in Wales; Hallsands, Happisburgh, Dawlish, and Great Yarmouth in England; and Benbecula in Scotland. The lowest score was one, and 64 cells received this value. CVI scores for the beach width parameter clearly indicated that the sites in England have greater vulnerability with respect to this parameter than those in Wales and Scotland. Considerable variance exists among the **dune width** CVI values for the 158 shoreline cells. The average CVI score was 3.5, and the highest score was 4, which was recorded for 124 cells (78%). Those that received high scores were found at Spurn Head, Hallsands, Dawlish, Happisburgh, Great Yarmouth, and Skegness in England, as well as at Benbecula. The dune width CVI scores indicated that the English sites are more physically vulnerable than those in Scotland and Wales. The average CVI score for **coastal slope** was 3.6, and the highest score was recorded for 129 cells (81%). Most of the high values were again recorded at Llanelli and Port Talbot in Wales; Happisburgh, Dawlish, Great Yarmouth and Skegness in England; and Benbecula in Scotland, whereas the minimum values were recorded at Aberystwyth in Wales and Hallsands and Lynmouth in England. The CVI scores for coastal slope reflect high vulnerability throughout the survey area, as well as some site-specific variations.

Considerable variance exists among the CVI values for distance of **vegetation behind the back beach**. The average CVI score was 2.7, and the highest was 4, which was recorded for 38 cells (24%). Most of the highest values were recorded at Port Talbot in Wales and Great Yarmouth and Skegness in England. The lowest CVI value was one, and this value was recorded for Llanelli and Hallsands in England and Benbecula in Scotland. Seventy-five cells (47%) received the lowest values. The CVI scores for the distance of vegetation behind the back beach clearly indicated that England and Wales have the highest vulnerability in terms of vegetation. The average CVI score for the **distance of built structures** behind the back beach was 2.8, and the highest CVI score was 4, which was recorded for 48 cells (30%). The highest values were recorded at Aberystwyth and Llanelli in Wales; Hallsands and Happisburgh in England; and Benbecula in Scotland. The lowest score was 2, which was recorded for 74 cells (46%) cells, and 15 cells did not contain built structures. A considerable variance exists among the rocky outcrop CVI values for the 158 shoreline cells. The average CVI score for **rocky outcrop** was 3.6, and the highest CVI score was four, which was recorded for 124 cells (78%). Most of the highest values were recorded at Llanelli in Wales; Great Yarmouth, Skegness, and Dawlish in England; and Benbecula. Of the sites surveyed, the CVI scores for rocky outcrops suggest that locations in England require more coastal protection measures than those in Wales and Scotland. The average CVI score for **sea defences** was 3.5, and the highest CVI score was 4, which was recorded for 84 cells (59%). The highest values were recorded at Port Talbot in Wales; Great Yarmouth, Skegness, Dawlish, Lynmouth, and Spurn Head in England; and Benbecula in Scotland. Of the sites surveyed, the CVI scores for sea defences highlight the considerable vulnerability of the English sites and their need for additional coastal protection.

4.1.2. Overall CVI scores

Considerable variations (Fig. 4) exist between the 158 cells. The average value was 20.33, which corresponds to the high category.

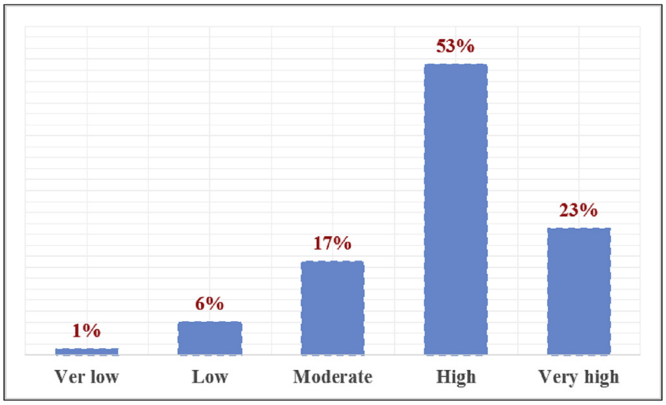

Fig. 4. Percent distribution of (PCVI) relative vulnerability categories.

However, the maximum PCVI value (28) was obtained for Great Yarmouth, while the lowest (10) was obtained for Lynmouth. More than 22% (n = 35) of cells were rated as having extremely high vulnerability (24–28), and 52% of the cells were rated as highly vulnerable (19–23). In addition, 17% of the cells were found to be moderately vulnerable (16–18), but the overall CVI scores clearly indicated that the physical vulnerability of selected regions in the UK is either extremely high or high.

PCVI values are indicative of overall vulnerability and suggest that the English case study locations are more vulnerable than those in Wales and Scotland. Some coastal cells have few or no dunes (Lynmouth and Llanelli) and others have few or no rocky outcrops (Lynmouth and Spurn Head). For these reasons, most shoreline measurements were at the lower end of the scale, falling between low and moderate, and relatively few cells were classified as being high in terms of relative vulnerability. However, the PCVI scores of each region are relatively high. After the PCVI scores were calculated, these scores were aggregated to rank the eleven coastal vulnerability zones to identify the overall severity of coastal vulnerability. For example, Lynmouth is represented by coastal cells 15 to 18, and the value of each coastal cell was added together to get a total value for Lynmouth, i.e., 21 + 18+19 + 17 = 75. This procedure was replicated for all 11 coastal sites (Table 7). This kind of assessment is helpful for decision makers and policy makers to identify the severity of vulnerability at particular sites. Based on this kind of assessment, Great Yarmouth was found to be the most vulnerable, with a CVI score of 670, and Aberystwyth and Port Talbot were found to be the least vulnerable. Crucially, these cumulative scores provide the opportunity to consider management options (e.g., restricting coastal infrastructure development, the construction of coastal walls, or the construction of artificial dunes) where physical vulnerability is highlighted. It should also focus efforts for more extensive future research at such sites.

Table 7
Cumulative scores of PCVI.

Site Name	PCVI Score
Great Yarmouth	670
Skegness	508
Llanelli	475
Port Talbot	410
Benbecula	326
Dawlish	199
Happisburgh	181
Hallsands	174
Spurn Head	132
Aberystwyth	84
Lynmouth	75

Table 8
Fiscally vulnerable coastal site locations and numbers of associated cells.

Site Name	Shoreline length (km)	No. of 1-km cells	FCVI Score
Great Yarmouth	13	13	293
Skegness	18	18	249
Port Talbot	12	12	202
Llanelli	12	12	160
Dawlish	6	6	128
Benbecula	5	5	78
Happisburgh	4	4	64
Aberystwyth	2	2	49
Hallsands	4	4	47
Lynmouth	2	2	27
Spurn Head	2	2	22

4.2. FCVI analysis

As described in Section 3.2, the chosen coastal locations were each subdivided into 1 km cells along the shoreline frontage. In total, 80 cells along 80 km of coastline were identified (Table 8). Three locations in Wales that represent circa 26 km of coastline (26 cells), seven locations in England that represent 49 km (49 cells) and one area in Scotland with circa 5 km of coastline (5 cells) were chosen based on the PCVI analysis.

The FCVI permitted the ranking of the eleven coastal sites in order of the severity of fiscal vulnerability (Table 8). The eleven sites represent a total economic risk of > £22 billion under current scenarios, which includes > 50,000 residential properties (0.2% of the total for the UK) and > 6000 commercial properties (0.37% of the total for the UK). Furthermore, approximately 118400 people (0.2% of the UK's population) are at risk of displacement from flooding, etc. (Kantamaneni, 2016b). As shown in Table 8, Clear differences existed in the rankings of the eleven sites. Based on the cumulative scores, Great Yarmouth has high fiscal vulnerability, and Spurn Head has the least vulnerability. However, the average scores differed from the cumulative scores; accordingly, Aberystwyth has high fiscal vulnerability. This kind of assessment help to evaluate the vulnerability of particular sites from different perspectives.

4.3. Comparison of the average PCVI and the FCVI

Comparison of the drivers of the PCVI and FCVI values allows for better assessment of the overall levels of vulnerability of the different sites. The average PCVI and FCVI scores gave interesting results (Table 9; Fig. 5). Great Yarmouth's PCVI (24) is higher than its FCVI (22.3), but Aberystwyth's FCVI (24.5) is higher than its PCVI (17). At Spurn Head, the physical vulnerability is much higher (22) than its fiscal vulnerability (11), probably due to the lack of coastal defences and rocky outcrops, as well as the low number of properties. Port Talbot is an interesting site because it's PCVI and FCVI values are more or less the same, 17 and 16.8, respectively. For Hallsands, the physical vulnerability is much higher, as indicated by a PCVI score of 22, compared

Table 9
Average PCVI and FCVI values.

Site	PCVI	FCVI
Great Yarmouth	24	22.3
Happisburgh	23	16
Spurn Head	22	11
Hallsands	22	11.7
Skegness	22	13.8
Benbecula	22	15.6
Lynmouth	19	13.5
Dawlish	18	21.3
Llanelli	18	13.3
Aberystwyth	17	24.5
Port Talbot	17	16.8

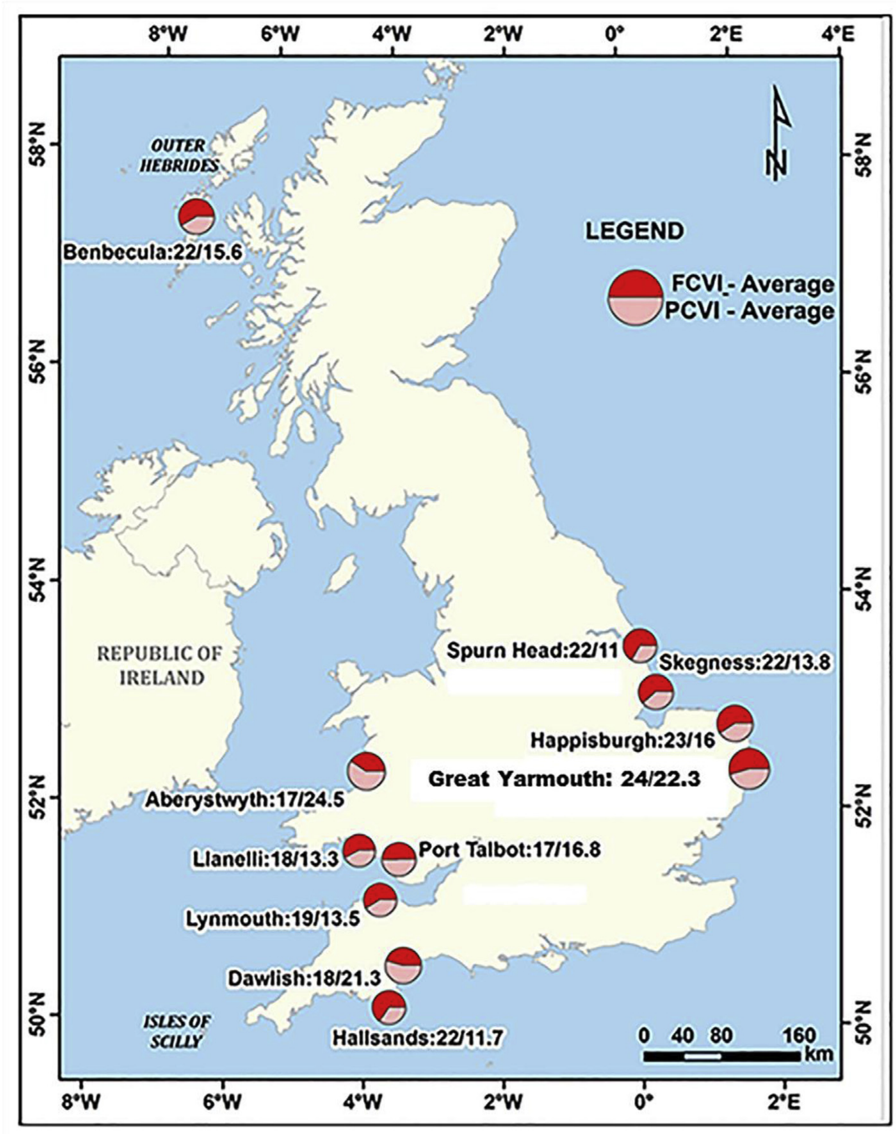

Fig. 5. A bubble cartogram highlighting the average values of economic and physical vulnerability superimposed upon a map of the UK.

with fiscal vulnerability; its FCVI is 11.7. Furthermore, Dawlish's fiscal vulnerability score (21.3) is greater than its physical vulnerability score (PCVI = 18), which can be explained in terms of the number of expensive properties located near the shoreline. To assess potential links between the PCVI and the FCVI, and to obtain a better understanding of both the magnitudes of change and the economic consequences, Table 9 shows the PCVI and FCVI values for each of the eleven areas, from which Fig. 5 was produced.

Fig. 6 represents the sites using graphical quadrants according to four categories: low physical/low economic, low physical/high economic, high physical/low economic and high physical/high economic categories. Therefore, this graphical representation can be used at various scales to compare coastal areas, which in turn will help decision-makes prioritise limited funding to protect the areas that are most at risk.

4.4. CCVI

Further interpretation of the PCVI and FCVI values was undertaken via the formulation of a combined coastal vulnerability index (CCVI), as previously described in the methodology section. The PCVI and FCVI values were combined to form a CCVI for each site, as shown in Table 10. For example, Spurn Head's combined physical vulnerability score was 132, based on 6 cells, whereas its overall fiscal vulnerability score of 22 was obtained from 2 cells.

$$CCVI = \frac{(132/6 + 22/2)}{2}$$

$$CCVI = \frac{(22 + 11)}{2} = 16$$

The resulting vulnerability score of 16 suggests that this coastal location is at moderate risk. In this case, the management response would suggest that further studies be carried out before any long-term proposals are formulated.

Results showed that Great Yarmouth has the highest overall combined coastal vulnerability, as demonstrated by its CCVI value of 23, followed by Aberystwyth (21), Happisburgh and Dawlish (20). Llanelli and Lynmouth both have the lowest CCVI value (16) with Spurn Head and Port Talbot just above with a CCVI value of 17. Table 10 indicates that, overall, the English sites were generally the most vulnerable, although that result is also a function of number of sites assessed. Moreover, Spurn Head has a high physical ranking but a low economic

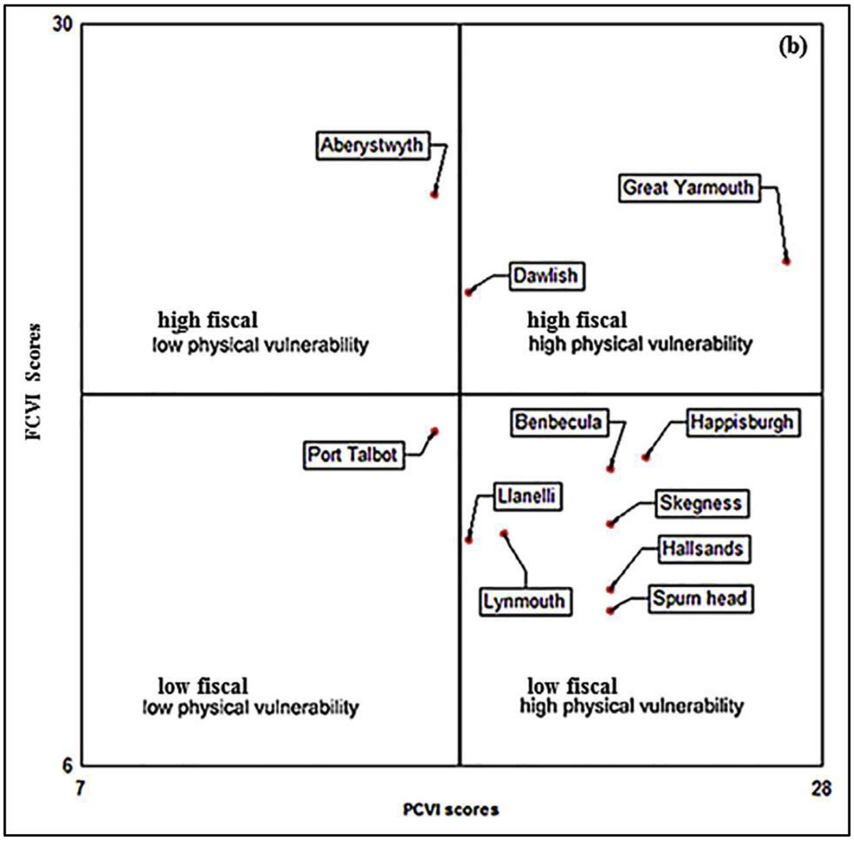

Fig. 6. Graphical representation of PCVI and FCVI.

Table 10
CCVI values and site ranking.

Site	CCVI	Rank
Great Yarmouth	23	1
Aberystwyth	21	2
Happisburgh	20	3
Dawlish	20	3
Benbecula	19	5
Skegness	18	6
Hallsands	18	6
Port Talbot	17	8
Spurn Head	17	8
Lynmouth	16	10
Llanelli	16	10

ranking, which is influenced by its sand and shingle spit morphology that is not conducive to construction and population growth. The Port Talbot and Llanelli regions are centred on industry; consequently, they contain large numbers of residential and commercial properties. However, these areas are generally protected by sea defences, although the sustainability of these protection measures has been questioned by both Phillips and Williams, 2007 and Denner et al. (2015). In these cases, the protection measures are a function of the industrial importance, resulting in similar physical and economic rankings. To enable easy reference, the CCVI results are superimposed upon a map of the UK (Fig. 7).

5. Discussion

In the present study, a modified PCVI based on key elements of Palmer et al. (2011) and Denner et al. (2015) was developed and used to assess 11 coastal hotspots of the UK. Based on physical variations of 11 locations, an additional two novel physical parameters i.e. distance of built structures behind the back beach and coastal defences, were included. The selection of physical parameters can be complex, due to the number of driving forces within specific coastal environments. In the case of Llanelli, the movement along deep-water channels had an important effect on the erosion of the northern shore; however, the presence of dunes, rocky outcrops and sea defences played vital roles in shoreline protection, which delayed the consequences of erosion becoming evident (Phillips et al., 2009). However, in some places, such as Benbecula in Scotland and Aberystwyth in Wales, there are no dunes. In general, these locations are more vulnerable than areas that have dunes. Physical vulnerability varies according to location in the UK, despite all eleven sites having suffered the consequences of coastal storms and flooding. The site with the greatest vulnerability was shown to be Great Yarmouth.

The highest average PCVI value was recorded at Great Yarmouth (24), and the lowest values were noted at Port Talbot and Aberystwyth (17) (Fig. 8), which indicates that all eleven sites are subject to damage from storms. Values are not cumulative and the chart only reflects the comparative nature of vulnerability. The importance of physical and fiscal vulnerability is shown in Fig. 6 which defines implications. The average PCVI scores suggest that Great Yarmouth and Happisburgh have the highest vulnerability, because of the sites where the majority of properties are located within 1 km of the coastline are in Aberystwyth, Dawlish, Hallsands and Skegness. Flooding and erosion were the two major issues impacting the coastal areas; in locations such as Aberystwyth and Llanelli, the addition of new developments in these areas of high vulnerability will increase pressures, leading to even greater economic losses from flooding and storm damage (Phillips et al., 2009; Denner et al., 2015; Kantamaneni et al., 2015). However, the cumulative scores differ slightly, such that Great Yarmouth and Skegness have high PCVI values (670 and 508, respectively). Cumulative scores provide the opportunity to consider management options where physical vulnerability is highlighted. It should also focus efforts for

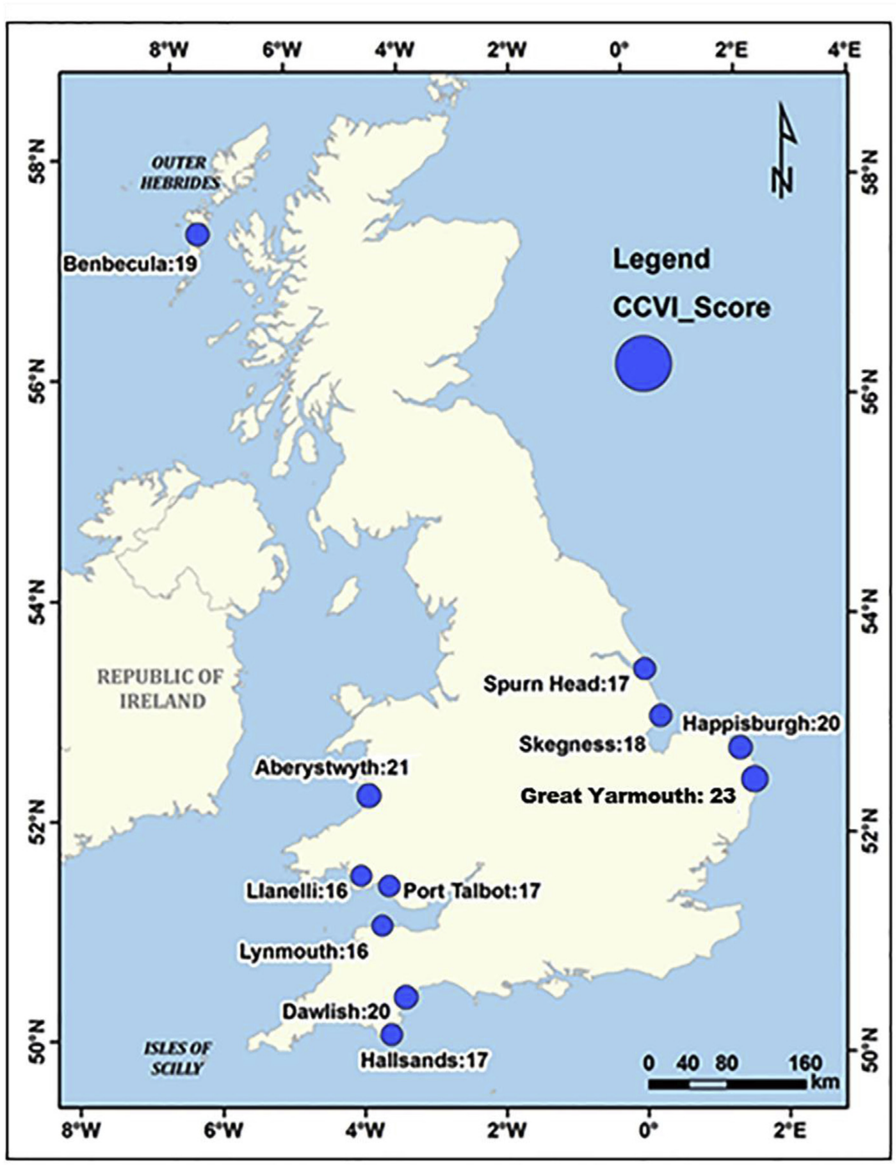

Fig. 7. Map of combined coastal vulnerability index (CCVI) values.

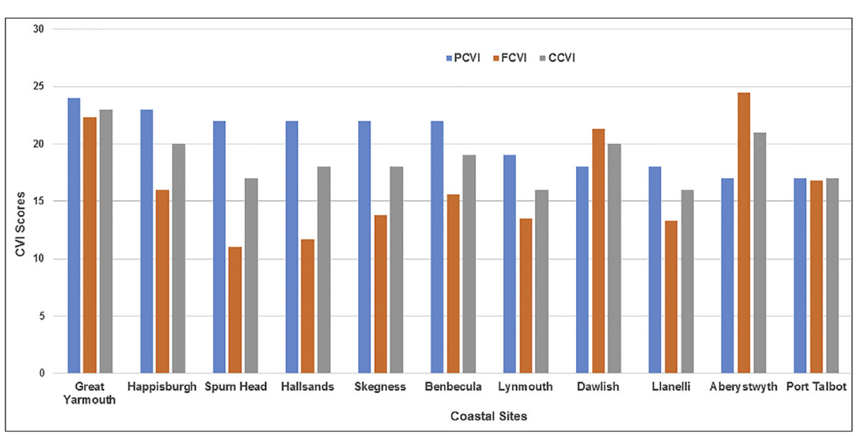

Fig. 8. Representation of coastal vulnerability indices.

future research on a wider scale at such sites.

However, the CCVI values suggest somewhat different results. Great Yarmouth has the highest vulnerability, because of its high population and rapid coastal infrastructure expansion; however, Llanelli has the lowest vulnerability, due to the presence of coastal defences, such as coastal walls and rocky outcrops.

The use of the PCVI, the FCVI and the CCVI in assessing the vulnerability of specific sites can identify shorelines that are less vulnerable. It can therefore inform future planning and redevelopment decisions. It is recognised that the identification and assessment of socio-economic and ecological components and their association with zones of high vulnerability is also significant and requires consideration when assessing coastal zone vulnerability and management options. These aspects are subjects of on-going research, but this method of estimating vulnerability will ultimately allow cost-benefit analysis. The results of this research will improve understanding of both the physical and the economic consequences of changing environmental conditions, particularly in highly populated, low-lying areas, and may be used to inform the effective planning of coastal management strategies in both physically and/or economically important regions worldwide.

6. Conclusions

Appraisal of coastal vulnerability from various perspectives offers specific results that are supported by evidence. Results of the present study have to be viewed with a degree of caution, as data acquisition was a function of the extent of coastline being assessed. The selection of physical parameters used to develop a PCVI was complex, due to a number of driving forces that operate within specific coastal environments. Dunes, rocky outcrops and sea defences play a vital role in coastline protection, by delaying the consequences of erosion becoming evident. However, in some places, there are no dunes or rocky outcrops and these locations are generally more vulnerable. Modifications to the methodology included sea defences, because physical interventions make the shoreline less vulnerable. The highest PCVI value was determined at Great Yarmouth, and the lowest was at Aberystwyth, which suggests that all eleven sites are subject to damage from storms. PCVI scores also suggest that the Great Yarmouth and Happisburgh shorelines have the highest vulnerability, owing to postglacial adjustment, sea-level rise and relatively "weak" underlying materials, as well as having vulnerable areas where the majority of properties are located close to the coastline, such as Aberystwyth, Dawlish, Hallsands and Skegness. The FCVI was determined from six economic parameters that were assessed on a site/coastal location basis. When applied to the eleven selected coastal areas, results showed that fiscal vulnerability varies both within and between sites. Great Yarmouth had the highest FCVI and urban areas were generally most vulnerable, given that they have larger populations than rural communities. The importance of understanding population numbers at risk was recognised for both physical and socio-economic aspects of coastal research. Aberystwyth, Great Yarmouth and Dawlish received the highest FCVI values with respect to site value, the numbers of commercial and residential properties and population numbers, while Spurn Head and Hallsands were identified as having the lowest economic vulnerability. Site values of the two indices (PCVI and FCVI) were compared to estimate the relative severity of physical and economic vulnerability. Importantly by comparing these indices, coastal areas fell into one of four categories which visually informs risk and furthermore, they can be further combined to produce the CCVI. Therefore, as demonstrated by CCVI values, Great Yarmouth has the highest combined vulnerability, followed by Aberystwyth, Happisburgh and Dawlish. Conversely, Llanelli and Lynmouth have the joint lowest CCVI value. Consequently, CCVI provides a simple to use shoreline monitoring tool, which will benefit the range of stakeholders from coastal policy makers to non-technical members of the general public. The model enables risk assessment at local, regional and international scales, as it identifies vulnerable locations, thereby facilitating the development of management strategies to improve coastal resilience under various sea level rise and climate change scenarios.

Conflict of interest

This manuscript has not been previously published and is not under consideration in the same or substantially similar form in any other peer-reviewed media. To the best of my knowledge, no conflict of interest, financial or otherwise, exists.

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